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SPUTNIKS AND METEORS

-USSR-

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SPUTNIKS AND METEORS

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[Following is the translation of an article by B. Yu. Levin in Meteoritika (Meteoritics), Vol XVIII, Moscow, 1960, pages 20-25.]

The launching of artificial earth satellites, first achieved by the Soviet Union in 1957, opens up before specialists on meteoric materials completely new possibilities for the study of the finer meteoric dust. At the same time these students are more insistently than ever before confronted with the problem of the destruction of sputniks [by] the impact of meteoric particles. An answer on the basis of available information must be given immediately, in order that the solution may be refined in the future by means of new data obtained through the use of the sputniks themselves.

The problem of meteoric danger falls into two categories: first, there is the question of shell penetration and more serious damage by sufficiently large meteoric particles; the second problem concerns the gradual destruction (erosion) of the shell through the impingement of numerous tiny particles, each of which inflicts a very small dent (abrasive action).

We will limit ourselves to an examination of the first question.

At a velocity of tens of kilometers per second, a particle can penetrate a layer of metal having a thickness one order greater than its diameter. It is not known, however, whether the possibility of penetration depends on the momentum I = Mv of the oncoming particle or its energy

$$E = \frac{Mv^2}{2},$$

or on some other combination of mass and velocity. Whipple (4) calculates the penetration danger by assuming that the entire energy of the particle is spent on the removal o[illegible] material from a right circular cone having an apex ang[illegible] of 60°. This gives a depth of penetration

$$d = \left(\frac{9}{\pi \rho' \zeta}\right)^{1/3} E^{1/3},$$

where ρ' is the density of the shell, and ζ is the energy required to remove the material and taken as equal to the heat of melting. According to this formula, a spherical pa[illegible] ticle of density $\rho = 2$ grams/centimeter^3 and velocity $v =$ 40 kilometers/second will penetrate aluminum to a depth 10 times its diameter.

The supposition as regards indentations of the same form is unfounded. At the same time, there are other approaches to estimating the penetration with less of a dependence on velocity. For this reason we shall examine two variations, assuming that the penetration velocity of a particle is a function of its moment I or its energy E.

The penetration danger of course depends on the thickness and composition of the shell, which may be different for each satellite. For purposes of general orientation in the problem of the danger of penetration by meteoric particles, we shall examine, for example, an aluminum shell 2 millimeters thick, and will consider as penetrative (at $v = 40$ kilometers/second) collisions with particles 0.2 millimeters in diameter and over, i.e., particles with mass $M \geqslant 8 \cdot 10^{-6}$ grams ($\rho =$ 2 grams/centimeter^3). At other velocities, we shall con[illegible] as penetrative collisions with particles having a mom[illegible] $I \geqslant I_o = 8 \cdot 10^{-6} \cdot 40 \cdot 10^5 = 32$ gram-centimeters/second in one instance, or an energy $E \geqslant E_c = \frac{1}{2}\, 8 \cdot 10^{-6} (40 \cdot 10^5)^2 = 6.4 \cdot 10^7$ ergs in the other.

The main source of error in calculations of the pene[illegible] tration danger is the great uncertainty in estimating the masses of meteoric particles (Table 1).

Table 1: **Masses of Meteoric Particles Producing a Meteor of Null Stellar Magnitude at $v = 40$ kilometers/sec.**

Watson (1)	0.65	grams	(0.25 grams at $v =$ 55 km/sec)
Whipple (4)	1.25	"	
Whipple (2)	0.02	"	(0.04 grams at $v =$ 31 km/sec)
Levin (3)	0.055	"	

The dynamic method, based on measurements of deceleration, seems uncertain due to the impossibility of taking into account the fragmentation of meteoric bodies. For this reason, it appears more correct to use masses determined by the photometric method. On the basis of the "photometric masses" of 117 meteors (photographed at the Harvard Observatory) obtained by Jacchia (6), using Opik's numerical value for the luminosity coefficient [see Note], the author found that a meteor of null stellar magnitude at v = 40 kilometers/second is created by a particle of mass 0.055 gram (3). In 1952 Whipple assigned a mass of 1.25 grams to such a particle -- 23 times greater than that of the author, whi[le] in 1954 his estimate was 0.02 grams, i.e. 4 times sma[ller] than the author's (see (2)). [Note: In 1955, hav[in]g reexamined the problem of the coefficient of luminosity, Opik arrived at a new value $1\frac{1}{2}$ times smaller than the former one.]

On the basis of the author's mass estimates, danger is posed by particles creating meteors of up to the 9th stellar magnitude (at v = 40 kilometers/second); on the basis of Whipple's first estimate, the danger is posed by particles giving rise to $12\frac{1}{2}$ stellar magnitude meteors. (We have in mind here the absolute stellar magnitudes corresponding to the maximum brightness of the meteor, which is proportional to the initial mass of the meteoric body.) While with the author's estimates it is possible to determine the numbers of dangerous particles by means of ordinary statistical observations of ordinary and telescopic meteors or radar observations, Whipple's estimates require one to resort to extrapolation into the area of the even weaker meteors, which cannot practically be covered by observations. [see Note]

[Note: As the author was preparing his report for publication, he came into contact with Whipple's new work (5) in which the mass of a meteoric particle giving rise to a meteor of null stellar magnitude is given as 25 grams (at v = 28 kilometers/second). After recalculation for v = 40 kilometers/second (with the assumption that the light intensity is proportional to Mv^3), a mass of 11.4 grams, i.e., 9 times greater than Whipple's 1952 value, is obtained. Examin[in]g the penetration of a 0.8 millimeter aluminum shell i[n] light of this new estimate, Whipple is obliged to [re]ly on estimated counts of 18-19 stellar magnitude meteors.]

The new estimate of meteoric body masses combined with their improbably low density (ρ = 0.5 grams/centimet[er³]) is based on heretofore unpublished results of photographi[c]

observations made at Harvard.]

If the ratio of the number of meteors in this neighborhood of stellar magnitudes is $\varkappa = 2.5$, then the author's meteoric mass estimates yield a calculated penetration danger 23 times less than is obtained with Whipple's 1952 estimates. If, moreover, $\varkappa = 3$, then the penetration probabilities will differ by 42 times [see Note]. [Note: With Whipple's new mass estimates (5) the ratio of probabilities turns out to be 15-25 times greater.]

Insofar as meteoric particle velocities differ among themselves only by several times (atmospheric entry velocities fall within the limits of from 11 to 73 kilometers/second; velocities of satellites and rockets moving relatively to these particles vary within somewhat wider limits), the error arising from our ignorance of whether penetration depends on momentum or energy is much less than the errors due to a poor knowledge of meteoric masses.

As was explained elsewhere (3), a great number of meteors in the main meteoric streams are, as a rule, travelling with a great heliocentric velocity; this fact permits the observation of meteors formed by numerous fine particles. The spatial density of meteoric aggregates (computed to a definite mass limit) is less than the spatial density of meteoric bodies which give rise to sporadic meteors. (We usually regard meteors of weak, poorly defined streams as belonging to the latter type [see Note].). It is only in the denser aggregates, an encounter with which leads to heavy meteor showers, that the spatial particle density is greater than that of the sporadic background. [Note: According to Whipple, practically all sporadic meteors belong to the weak streams, i.e. are of cometic origin, while the proportion of particles of asteroidal origin is insignificantly small. The observational material which serves as the basis for this conclusion is as yet unpublished. It is possible that the role of particles of cometic origin has been overestimated.]

The light intensity of meteors is roughly proportional to the cube of their velocity, and it is this dependence, which, in combination with the sharp rise in the number of particles with progressively decreasing size, determine the great numerical frequency of meteors in the rapid streams. At the same time, the particles creating the sporadic background travel largely along straight orbits and have low velocities relatively to the earth. Energy is proportional to the square, and momentum -- to the first power of velocity.

For this reason, even if the penetration danger is a function of energy, and even more so if it depends on momentum, the increase in danger upon encounters with meteor streams is, as a rule, considerably less than the increase in the apparent numerical frequency of meteors.

During the motion of the satellite along its orbit, the danger posed by a given meteoric stream varies significantly. In the first place, in a certain portion of its orbit the satellite is shielded from the stream by the earth itself (unless, of course, the orbital plane is perpendicular to the direction on a visible radiant). In the second place, a change in the direction (and magnitude) of the satellite's orbital velocity alters the relative ("sputnikcentric") velocity of the meteoric particles. For the purposes of characterizing the mean danger-probability on a portion of the orbit unshielded by the earth with sufficient precision, it may be assumed that the relative particle velocity is equal to the atmospheric entry velocity of the particles, i.e., their heliocentric velocity as increased by the earth's gravity.

The danger posed by particles which give rise to sporadic meteors turns out to undergo little alteration during the satellite's revolution about the earth. Of all the numerous particles trailing the earth, only the larger ones have sufficient momentum or energy due to their low relative velocity to pose any danger. At the same time, although the number of particles moving head-on is considerably less (up to a certain mass level), their great velocity relative to the earth is such as to make the small ones dangerous.

In order to make a quantitative comparison of the danger posed by sporadic meteoric particles on the one hand and stream particles on the other, as well as to compare the streams to each other, we shall first of all compute the conditional danger so chosen that it can be determined with a great deal of certainty on the basis of statistical meteoric observations and is independent of the great uncertainty introduced into estimates of the actual danger by the unsatisfactory knowledge of meteoric particle masses and of the considerably smaller uncertainty connected with the extrapolation of the numerical meteor frequency beyond the limits of the directly investigated magnitude interval.

Let us denote by M^* the mass of a meteoric particle which, upon vertical entry into the atmosphere with a velo-

city v = 40 kilometers/second creates a meteor of 4.3 stellar magnitude. As long as such a stellar magnitude corresponds to the effective limit of visual statistical meteor observations, these observations afford the possibility for a very precise determination of the spatial density of particles with mass $M \geqslant M^*$. The author used this fact earl... (3). Using the data obtained in this way, it is possible to calculate the probability of collisions in which the momentum I (or the energy E) will be greater or equal to momentum I* (or energy E*) of a particle with mass M* moving at a velocity of 40 kilometers/second. The results of the calculations are presented in Table 2, giving the probability P_c of a collision with a 1 meter^2 surface area in 1 year.

<u>Conditional Probabilities P_c of Meteoric Collisions</u> Table 2

Streams	Number of meteors/ hour	Number of particles with $M \geqslant M^*/10^9$ km^2	P_c/meter^2 per year	
			$I \geqslant I^*$	$E \geqslant E^*$
Quadrantid	40	45	$0.03 \cdot 10^{-4}$	$0.06 \cdot 10^{-4}$
Lyrid	10	8	0.11	0.16
δ-Aquarid	36	7	0.35	0.20
Perseid	65	15	0.42	0.24
Orionid	12	1	0.04	0.03
Taurid	5	30	0.20	0.14
Leonid	8	1	0.04	0.08
Geminid	60	130	1.35	1.2
Bootid	60	1,400	4.8	2.2
Cetid	100	200	2.6	1.8
Leonid 1866	6,000	800	93	60
Andromedid 1875 and 1885	6,000	140,000	440	120
Draconid 1933	15,000	180,000	780	400
Draconid 1946	30,000	360,000	1000	910
Sporadic	10	1,100	{1.9 {2.5·10^{-4}	0.8* 0.6·10^{-4}

* Center of morning hemisphere (apex at zenith).
** Center of evening hemisphere (antiapex at zenith).

For the main meteoric streams, even in the epochs of their maximum, the probability of penetration by particles belonging to the stream remains several times smaller than the mean probability of penetration by sporadic particles

that the distribution of particles according to mass follows the $1/M^2$ law very closely, i.e. the number of particles with mass greater than M is proportional to 1/M. Thus, the actual probability of penetration by particles giving rise to sporadic meteors is 125 times greater than the conditional probability as given in Table 2. Using a more intuitive formulation through the use of the formula $\Delta t = 1/P$, i.e. the mean time interval between two consecutive collisions with 1 meter^2 area, we obtain the following:

	Δt, in years	
	$I > I_0$	$E > E_0$
Apex at zenith	80	100
Antiapex at zenith	20	90

An analogous recalculation for the streams leads, as a rule to even lower collision frequencies -- on the order of one collision per several hundred years. In the denser portions of the Andromedid and Draconid aggregates, the mean time interval between dangerous collisions amounted to ½-2 months, while the entire duration of the earth's passage lasted just several hours.

It should not be forgotten, however, that the danger will turn out much greater if it should be found out that our assumed meteoric body mass is significantly lower than the actual one [see Note]. [Note: Whipple (5), taking M(0) = 11.4 grams, or 200 times greater than our value, draws the conclusion, that a 20-inch sphere with an 0.5-millimeter thick aluminum shell will be punctured once every 5 days, on the average.]

In conclusion, let us briefly direct our attention to the second problem of meteoric danger, namely to "the abrasive action" of meteoric collisions.

Collisions with minute dust particles incapable of puncturing the satellite shell must occur several orders more frequently than penetrative collisions. The number of specific collisions is of no interest in this case; what is important is the total mass of tiny particles hitting a unit surface area per unit time. This mass is proportional to the daily increase in the earth's mass due to the precipitation of fine particles, and may be expressed by means of the spa-

[see Note]. Of the major streams, only the Geminid str poses twice the danger. A similar, and even greater increase in danger occurs during certain unexpected heavy streams observed only on one occasion. As an example, Table 2 gives data for the Boötids observed on 10 June 1930, and the Ce-uids of 19 October 1935. A really significant increase in danger occurred only during the earth's passage through especially dense aggregates which gave rise to extremely heavy showers of Leonids, Andromedids, and Draconids. In such cases, for a very short period of several hours, the danger became tens and hundreds of times greater than the mean value determined by the sporadic background penetration probability. But since the sporadic probability is in effect continually, i.e., thousands of times longer than the time it takes the earth to pass through such extraordinarily dense aggregates, it is this sporadic backround which poses the major penetration danger for satellites. [Note: Changes in the spatial density of particles giving rise to sporadic meteors along the earth's orbit have been established in recent years. The density varies by 1½-2 times in either direction from the mean annual value.]

Having reliably established the major source of danger by examining the conditional probabilities, we must now estimate its absolute value. Unfortunately, at this point we cannot avoid introducing into our figures all of the uncertainty incumbent on estimates of meteoric masses.

If the mass of a meteoric body which gives rise to a meteor of null stellar magnitude at v = 40 kilometers/second is denoted by M(0), and if it is assumed that the intensity of light given off by a meteor is proportional to particle size, then

$$M^* = M(0) \cdot 2{,}512^{-4{,}3} = 1{,}9 \cdot 10^{-2}\, M(0).$$

With the value of 0,053 grams for M(0) found by the author, M* turns out to be equal to $1 \cdot 10^{-3}$ grams. At a density of 2 grams/centimeter^3, a spherical particle will have a diameter of 1 millimeter.

We previously agreed to consider as dangerous collisions with particles with a diameter exceeding 0,2 millimeters, i.e., with a mass smaller by 125 times. It is therefore necessary to take into consideration data on meteors weaker by about 5 stellar magnitudes. Radar observations of weak ("telescopic") sporadic meteors have led to the conclusion

4. F.L. Whipple, "Meteoritic Phenomena and Meteorites. Physics and Medicine of the Upper Atmosphere", 19?2.
5. F.L. Whipple, "The Meteoritic Risk to Space Vehicles", *Vistas Astronaut.* (Sympos. San Diego, Calif., Febr. 1957) London -- New York -- Paris -- Los Angeles, Pergamon Press, 115-124, 1958.
6. L.G. Jacchia, "A Comparative Analysis of Atmospheric Densities from Meteor Decelerations Observed in Massachusetts and New Mexico", *Harv. Obs. Techn. Rep.* No 4 = Harv. Repr. ser. II, 44, 1952.

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tial density of dust material.

Estimates of the spatial density ofdust material made on the basis of meteoric data approximations are extremely unreliable, since the size distribution function found for large particles is known to change with regard to the small ones. Errors involved in such an extrapolation are of the same order as the errors connected with an unsatisfactory knowledge of meteoric masses. Estimates of the dust material spatial density based on the photometric observation of zodiacal light and the Fraunhofer lines of the solar corona spectrum are also found to diverge by several orders in the works of various authors.

Despite of all the inaccuracy in estimates of the spatial density of the dust particles, the main reason for the uncertainty of conclusions regarding the rate of satellite shell erosion consists in a poor knowledge of the consequences of the collisions. If it is assumed that the extracted mass is on the same order of magnitude as the colliding particle, or that there is a local evaporation of the shell, then the removal of a 1-micron layer would require one thousand years (with a spatial density on the order of 10^{-21} grams/centimeter^3). If, on the other hand, we suppose that the entire impact energy is spent on the extraction of 10-micron particles from the shell, then a layer 1 millimeter thick can be eroded in the space of a few days. The actual state of affairs lies somewhere between these two extremes and is probably closer to the former.

It is highly probable that the problem of the abrasive action of meteoric collisions will be investigated less by laboratory methods than by observations of the satellites themselves.

The author wishes to express his gratitude to S.V. Mayeva, who calculated the probabilities given in Table 2.

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